APPENDIX B. REFINEMENT OF THE SAMMAMISH RIVER CE-QUAL-W2 TEMPERATURE MODEL AND APPLICATION TO LONG TERM SIMULATIONS

King County Department of Natural Resources

Technical Memorandum

TO: John Lombard / Director's Office

FROM: Curtis DeGasperi / WTD

DATE: December 21, 2001

SUBJECT: Refinement of the Sammamish River CE-QUAL-W2 Temperature Model and Application to Long Term Simulations

Executive Summary

A temperature model developed by John E. Edinger and Associates, Inc. (JEEAI), for predicting the temperature of the Sammamish River in response to various management scenarios was improved and set up to perform long term simulations of various temperature management scenarios. Model improvements included changes in the model configuration to better simulate the summer increase in water surface temperatures in the downstream river reach and incorporation of additional monitoring data not previously made available to JEEAI. The revised model was applied to improve upon the previous evaluation of management scenarios by:

- Focusing on the time of year when temperatures pose a significant threat to migrating adult salmon (August 1 - October 31), using weather and flow data from 1970-99 to represent a range of conditions experienced during that time of year. Management scenarios were previously evaluated based on a 2-day "worst case" period in July 1998 that is unlikely to occur when salmon are in the river.
- Using an "Index of Thermal Stress" to measure the cumulative effects of high temperatures on salmon, as recommended by biologists. The previous analysis focused on average and maximum temperatures during the "worst case" period.
- Better characterizing actual management scenarios under potential consideration.

This memo documents the latest model configuration/calibration and the results of long-term model simulations of fifteen temperature management scenarios. The memo also identifies further needed improvements in the model configuration, primarily at the downstream boundary. Additional recommendations for monitoring and modeling efforts are also included in this memo.

For brevity, not all of the tables and figures have been included with this memo. References are made in the text to additional tables and figures that are available on request.

Analysis of the different management alternatives results in a few key findings:

- Hypolimnetic withdrawal is the only strategy reviewed that can make large reductions in thermal stress on salmon where it is greatest--at the outlet of Lake Sammamish, where the river is currently fed by the warm upper layer (epilimnion) of the lake. Even the more conservative modeling of this strategy (Alternative 14) resulted in a 66.4% decrease in average thermal stress and a 34.8% decrease in maximum thermal stress at Segment 3 (above Bear Creek), compared to 7.0% and 3.6%, respectively, for the combination of all of the other strategies (Alternative 13).
- Averaged over the entire river, revegetation of riparian areas could significantly reduce thermal stress on salmon as plantings mature, but this benefit is cumulative--the greatest benefits are in the lower river, where thermal stresses are less severe. Still, other than hypolimnetic withdrawal, shade from fully mature riparian vegetation (Alternative 6) is the most effective single strategy reviewed to reduce thermal stress for salmon.
- A combination of strategies using reclaimed water (Alternative 12) could significantly reduce thermal stress on salmon, by roughly the same magnitude as fully mature riparian vegetation. Groundwater augmentation (Alternatives 3-5) could potentially be the most significant strategy, depending on the volume, temperature and location of the enhanced flows entering the river.
- Management actions affecting Bear Creek have significant consequences for thermal stress on salmon in the Sammamish River. Restoration of up to 5 cfs of creek flows (Alternative 8) and protection of riparian shading of the creek (Alternative 9) are particularly important for the portion of the river immediately downstream of the confluence of the creek and river.
- Uncertainty regarding the amount of current surface withdrawals from the river does not create significant uncertainty in evaluating management actions. The estimate of surface withdrawals can be doubled (Alternative 2, compared to Alternative 1) without large changes in predicted temperatures.

Introduction

This document describes the work performed by King County Department of Natural Resources (KCDNR) staff to extend the application of an existing river temperature model developed for the Sammamish River to simulate multiple years. The model has previously served as a management tool to assess the potential of various alternatives to reduce simulated July 27-28, 1998 river temperatures. Lower summer temperatures should provide improved habitat conditions for salmon that migrate through the river to tributary spawning areas. Based on the initial assessment results, a number of recommendations were made by JEEAI (Jain et al. 2000) that included (but are not limited to) the following:

- Change the configuration of the model to reflect two distinct stream reaches: an upper sloping reach and a lower flat-water reach representing the backwater from Lake Washington;
- Perform multi-year simulations of existing conditions and alternative management scenarios

to provide temperature predictions that are more relevant to salmon management and protection.

Background

Listing of Puget Sound chinook under the federal Endangered Species Act (ESA) has triggered an intensive effort to identify causes of salmon population declines and measures that can be taken to maintain or improve existing populations. Observed pre-spawn mortality of adult chinook in the Sammamish River led water quality managers to initiate a temperature monitoring and modeling investigation of the river (Martz et al. 1999). Following the initial investigation, the monitoring program and model were refined, and the model was updated to the latest version by JEEAI (Jain et al. 2000, Buchak et al. 2001). The model is a two-dimensional, laterally averaged, hydrodynamic and water quality model (CE-QUAL-W2 Version 3.0) supported by the U.S. Army Corps of Engineers Waterways Experiment Station (ACOE-WES) (Cole and Wells 2000).

The model was calibrated to 1999 late summer temperature conditions in the Sammamish River and used to evaluate potential temperature management scenarios. Management scenarios included:

- Reduction of surface water withdrawals
- Flow augmentation with cool groundwater released to specific river segments
- Creation of riparian shade
- Replacement of warm water inputs from the surface of Lake Sammamish with cooler bottom water withdrawn from the lake

The assessment of the potential effectiveness of each scenario was based on a comparison of 2-day average, minimum, and maximum temperatures for a relatively extreme 48-hr period — July 27-28, 1998. As pointed out by Jain et al. (2000), the use of a single extreme period (relatively low flow and high temperature) does not provide a realistic distribution of possible management outcomes based on the natural hydrological and meteorological variability of the system.

The modeling results and field data were also compared to the results of a Forward-Looking Infrared (FLIR) study conducted on September 2, 1999 (McIntosh and Faux 1999). The FLIR results provide a thermal image of river surface temperatures. This comparison indicated that although the existing model configuration reproduced the hydraulic backwater from Lake Washington, the model did not allow the development of a warm surface layer in the lower river reach below Blyth Park.

Objectives

The overall objectives of the work described in this report were as follows:

- Continue support of Sammamish River temperature management studies
- Reconfigure the model geometry to reflect at least two distinct stream reaches (a sloping

upper reach and a lower flat-water reach)
- Develop the capability to simulate multi-year time periods
- Re-evaluate selected temperature management scenarios using a multi-year simulation

Specific tasks to meet these objectives were:

1. Reconfigure the model geometry with at least two distinct stream reaches
2. Re-evaluate the model calibration to additional time periods beyond the July-September period used previously if additional data are available
3. Set up the reconfigured model to simulate an extended (multi-year) period of time
4. Run the model to develop a simulation of long term temperature variation under "existing" or "base" conditions
5. Rerun selected temperature management alternatives for the extended time period
6. Statistically summarize the model output in a manner consistent with temperature management guidelines for the protection of cold water fish
7. Compare the summarized modeled alternative results to the "base" condition results
8. Prepare a Technical Memorandum that briefly summarizes the available data and data processing steps, model evaluation/refinement/calibration steps as necessary, and model application results

Approach

The general approach to completing the above tasks included 1) initial model reconfiguration and testing and incorporation of additional data; 2) compilation, processing, and evaluation of data needed to perform long term model simulations; 3) and specification of the method to statistically summarize model output in a manner relevant to the protection of cold water fish. The work performed to complete these tasks is described below.

Model Reconfiguration

JEEAI noted inconsistencies between model-predicted and FLIR-observed surface water temperatures at the downstream end of the Sammamish River on September 2, 1999 (Buchak et al. 2001). JEEAI performed some initial model testing to identify the cause of this inconsistency and recommended that the model configuration be modified to reflect two distinct river reaches with different slopes. Therefore, the model geometry input file provided by JEEAI was modified from the single reach/slope configuration to a two reach configuration with an upstream sloping reach (with the same slope as the original JEEAI geometry) and a second downstream reach with zero slope. Plan and profile views of the revised model geometry are shown in Figures 1 and 2, respectively. The boundary between the two reaches (At segment 34 above Blyth Park) was selected based on the following:

- The JEEAI model configuration did not reproduce the river surface temperatures (measured using FLIR) below Blyth Park in Bothell on September 2, 1999
- Reasonably good model agreement was obtained between hourly river temperatures (measured using continuously recording thermistors) and model output at Blyth Park and at

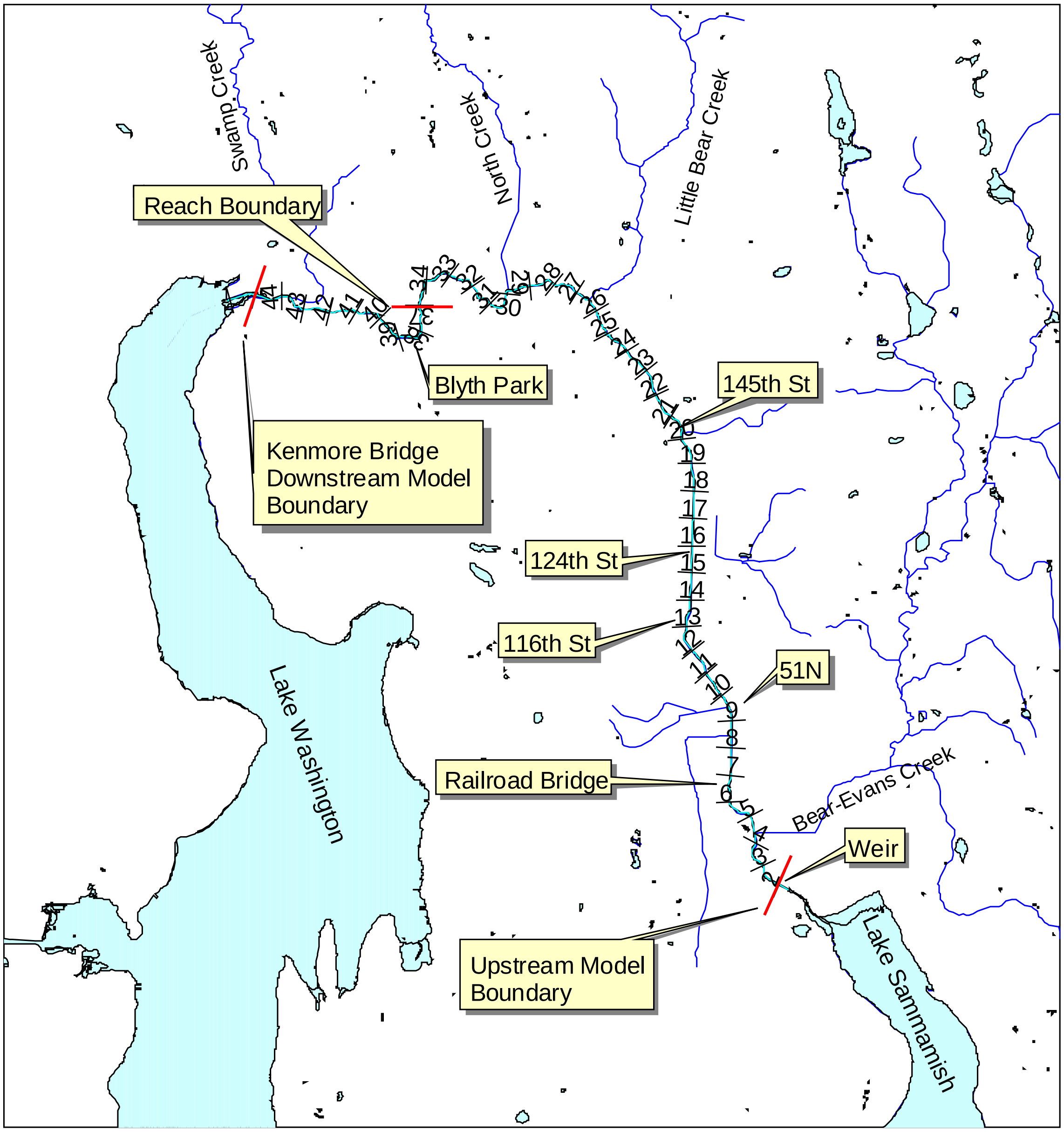

Figure 1. Revised Sammamish River CE-QUAL-W2 Model Geometry - Plan View.

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2000 0 2000 4000 6000 8000 10000 Feet

March 12, 2001

Legend

- Segment Boundaries
- Sammamish River
- Waterbody
- Tributaries

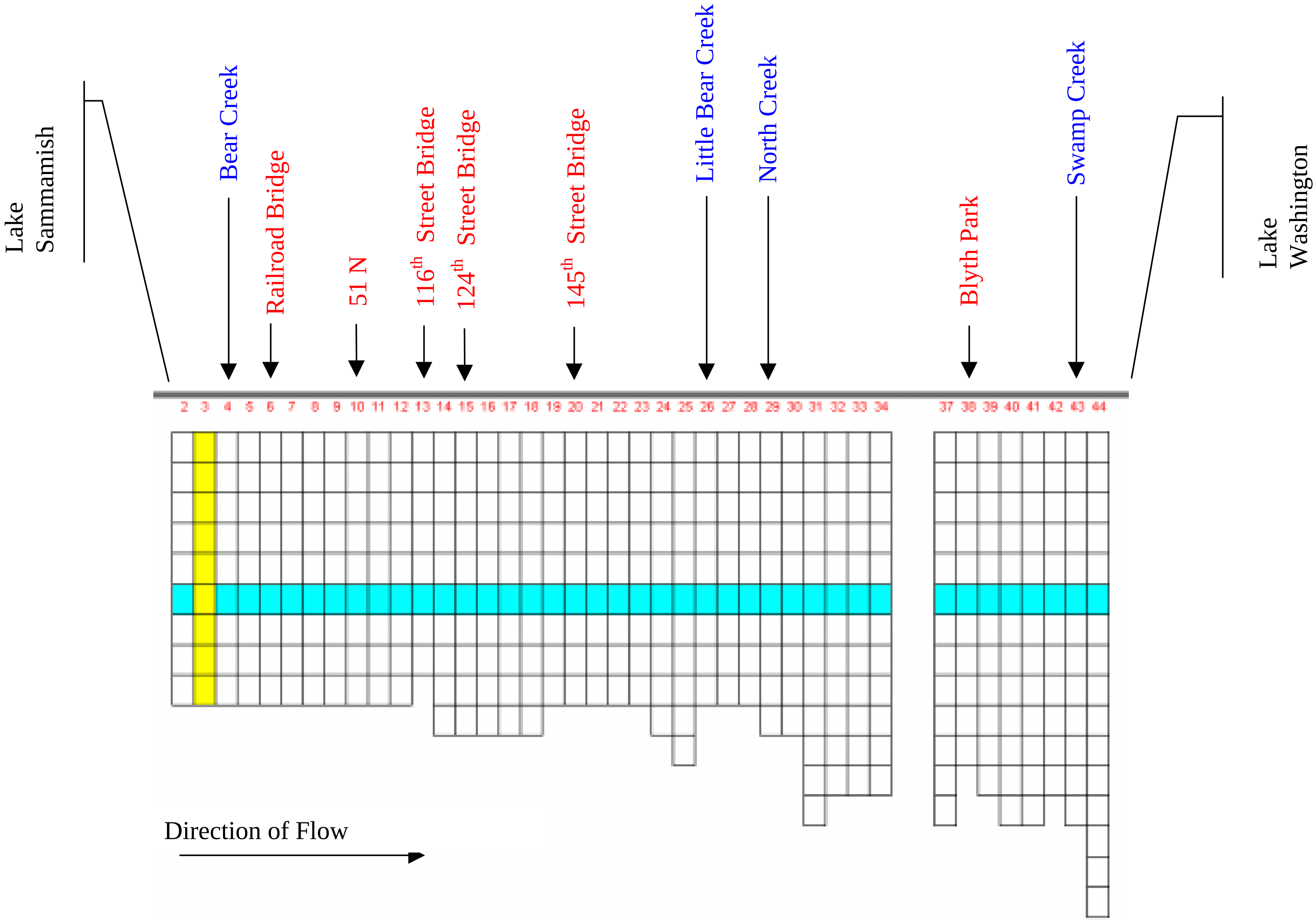

Figure 2. Revised Sammamish River CE-QUAL-W2 Model Geometry – Side View.

- four other locations upstream

In addition to changes in model geometry, the model was also improved through the compilation of additional 1999 data not previously made available to JEEAI. These data included observed tributary flows and temperatures recorded as part of the County's monitoring activities. For example, North Creek tributary flow and temperature was previously based on HSPF model results and the Swamp Creek temperature input was based on the records for Little Bear Creek due to the poor quality of the Swamp Creek temperature record. A table that provides model input source documentation and notes regarding data quality problems and solutions is available upon request. The additional data and supplemental analyses allowed the simulation of the entire 1999 calendar year. However, with the exception of additional hourly monitoring data collected by KCDNR at Station 51N below the Railroad Bridge in Redmond (4/30/99-10/11/99), model re-calibration and testing could not be extended beyond the period June 1 – October 22, 1999. Monthly grab monitoring data from two KCDNR stations [0486 (Marymoor) and 0450 (Kenmore)] and one Washington State Department of Ecology station [080B070 (Bothell)] were also obtained, but were not considered suitable (too infrequent) for use in model calibration.

Testing of the revised model geometry as a single waterbody with two reaches and as two waterbodies lead to the conclusion that the two waterbody setup provides more reliable predictions of river temperatures in the downstream reach boundary with Lake Washington. This conclusion was supported by discussions with Tom Cole (ACOE-WES) and Scott Wells (Portland State University), developers of the version 3.0 CE-QUAL-W2 model code (pers. comm.). The problem with the original single reach and two-reach setup (as a single waterbody) was due to the way the sloping water surface layer thickness is controlled by the model reference surface layer. The reference model surface layer is constant within a waterbody, which resulted in a reference layer that coincided closely with the water surface elevation in the upstream reach, but became progressively further apart as the water surface slope decreased. The two waterbody setup allows the reference surface layer to change between the sloping reach and the flat-water reach, minimizing the surface layer thickness at the downstream head boundary, and providing more realistic downstream conditions for modeling boundary driven hydrodynamics.

Model testing also suggested the need to add at least one additional downstream segment and perform further testing related to the potential need to divide the upstream reach into additional reaches with varying slope (or shorter segments) and test/refine the placement of the boundary between the two waterbodies. Additional revisions to the model geometry and further testing were beyond the resources allocated for the work described in this report. Further refinement of the model geometry, primarily to couple the river model to models of Lake Sammamish and Lake Washington, is recommended prior to performing additional applications

Long Term Model Setup

Once a satisfactory model geometry was identified, available data were compiled, evaluated, and processed to simulate a multi-year period. The length of the long term modeling period selected depended on the availability of hydrological and meteorological data. Model data needs include:

- Meteorological data (air temperature, dew point temperature, wind speed/direction, and cloud cover)
- Upstream flow and temperature at the Lake Sammamish weir
- Tributary flow and temperature (Big Bear, Little Bear, North, and Swamp creeks)
- Distributed tributary inflow (ungaged flow that includes ungaged tributary inputs and net groundwater flow to the river) and temperature
- Lake Washington (Kenmore) water surface elevation and temperature profiles

A table that summarizes long-term model data sources is available upon request.

- ***Meteorological Data***

Jain et al. (2000) provided meteorological data from Sea-Tac Airport for the period 1/1/1991 to 3/31/2000. Additional data available from Sea-Tac Airport were obtained from the National Climatic Data Center through a commercial vendor (EarthInfo, Inc.). The potential availability of meteorological data collected at local high schools as part of the King 5 TV Schoolnet program, and data collected by the University of Washington (UW) Department of Atmospheric Sciences was evaluated through discussion with Mark Albright, Research Meteorologist at UW (pers. comm.) Mark indicated that he routinely downloads and archives the SchoolNet data for use in synoptic evaluations of the Mesoscale Model Version 5 (MM5) climate-forecasting model. He also indicated that the UW also archives their climate records. However, he cautioned that there are data gaps in these records and various data are stored in different files and formats. He indicated that retrieval of the available data in the current archives would require additional time and resources beyond that available for this study.

Additional climate data sources have also been identified [e.g., City of Seattle water supply reservoirs, National Oceanic and Atmospheric Administration (NOAA) at Sand Point, Washington Department of Transportation (WSDOT) floating bridges, KCDNR Remote Underwater Sampling Stations (RUSS)]. The variety of data sources and needs, suggests the need for larger interagency cooperation and coordination to facilitate the storage and exchange of the climate information that is currently collected.

- ***Upstream Flow Boundary Condition***

Lake Sammamish water surface elevation records (Station 12122000) were obtained from the U.S. Geological Survey (1/30/39-1/17/01) and flow was derived from these records using the best available stage-discharge relationships for the appropriate historical time periods (Funke, D., pers. comm.). Further refinement of the current low flow stage-discharge relationship is recommended.

- ***Tributary Flows***

Tributary flows were modeled for the period 10/1/48-12/31/99 using existing County Hydrologic Simulation Program-Fortran (HSPF) watershed models that represent 1990s basin conditions (Hartley, D., pers. comm.). Tributary flows for Swamp, North, and Little Bear creeks were based on the Everett precipitation record and Big Bear Creek flow was modeled using the Everett precipitation record and a multiplier of 1.2. A 1.2 rainfall multiplier was used for the Big Bear basin to account for the generally higher elevations in this basin.

Distributed tributary flow was based on 1.7 times the flow in Little Bear Creek as in the modeling work conducted by JEEAI. The 1.7 multiplier is based on the ratio of the ungaged drainage area along the river to the drainage area of Little Bear Creek. The distributed flow is designed to account for ungaged inputs (net inputs) of surface and groundwater to the river. In lake and reservoir systems that are gaged at the inflow and outflow and also have recorded water surface elevations, it is relatively easy to estimate the contribution (or loss) resulting from ungaged sources of water. In the case of the Sammamish River, flow is measured at the upstream end and on the four major tributaries to the river. No measurements of flow at the downstream end are available (flow gaging at the downstream end is complicated due to the backwater effect from Lake Washington). It is recommended that further investigation of groundwater contributions to the river be conducted. A watershed model of the ungaged area along the river may also be useful in better quantifying the distributed runoff to the river.

- ***Lake Washington Water Surface Elevations***

Lake Washington (Kenmore and Ship Canal) water surface elevations [daily instantaneous value at 8 AM Pacific Standard Time (PST)] were obtained from the Seattle District of the ACOE (Herman, L., pers. comm.). The length of the Kenmore record was approximately 6 years (5/13/95-5/10/01), while the Ship Canal record extended back to 1941 (1/1/41-3/31/01). Comparison of the records from these two locations indicated that the record at the Ship Canal would require some adjustment for systematic seasonal differences between the two observation stations. There appeared to be an upward trend in the annual average and monthly average differences between the two stations from 1995 to 1999 and an upward trend in the Kenmore elevations, suggesting a problem with the Kenmore gage. The Seattle District ACOE did not feel that there were any long term systematic errors in the Kenmore elevation record but did acknowledge that periodic adjustments of as much as 0.2 ft have been made in the past (Herman, L., pers. comm.). Therefore, the monthly average differences between the two stations (1995-1999) were used to synthesize a Kenmore water surface elevation record from the Lake Washington Ship Canal record.

- ***Tributary Temperatures***

The tributary inflow temperatures were derived using the Response Temperature Model as previously applied by JEEAI to estimate the distributed tributary temperature (Jain et al. 2000). The Response Temperature Model is a relatively simplistic water temperature model. The "response temperature" is defined as the temperature a column of fully mixed water would have if surface heat exchange were the only active heat transfer process. The rate of surface heat exchange is computed from water depth, air and dew point temperature, wind speed, cloud cover, solar radiation, and atmospheric pressure. The model also incorporates a simple riparian shading algorithm and the effect of a steady groundwater inflow to allow adjustment of model temperature output to fit an observation time series. In general, the model variables for water depth, percent riparian shade, and fraction of groundwater were adjusted until no further improvement in model fit could be made. A groundwater temperature of 11 ^{o}C was used in the model, which is similar to the long term annual average air temperature recorded at Sea-Tac airport (10.8 ^{o}C for the period 1970-1999).

Available inflow and tributary temperature monitoring data were used to evaluate the reliability of the Response Temperature Model to synthesize the long-term inflow temperature records. It is envisioned that in the future as part of KCDNR's Sammamish-Washington Analysis and Assessment Program (SWAMP), more fully developed tributary basin models will provide predictions of flow and temperature for use as input to the Sammamish River model.

- ***Upstream Boundary Temperatures***

Originally, the long-term temperature of the Sammamish River at the upstream model boundary (Lake Sammamish weir) was to be derived using the Response Temperature Model (KCDNR 2001). However, because the seasonal temperature at the weir is the result of more complex heat exchange processes that take place within Lake Sammamish, the Response Temperature Model could not be calibrated well to the available 1999 weir temperature time series. It was decided a Lake Sammamish temperature model that simulated lake outlet temperatures might better reproduce the observed temperatures at the weir. Using available lake bathymetry data, a model of Lake Sammamish was set up for CE-QUAL-W2. The model consisted of 22 lake segments approximately 500-m long and 38 3-ft thick layers. Four additional shallow segments were added to represent the outlet from the lake to the weir. Inputs to the model included Issaquah Creek flow (USGS Station 12121600), calibrated Response Temperature Model simulation of Issaquah Creek and distributed tributary temperature [calibrated to limited Issaquah Creek data provided by D. Houck (pers. comm.)], distributed tributary inflow based on a flow balance between inflow, outflow, and lake storage, and the Sea-Tac meteorological data. This approach still did not reproduce the 1999 weir temperature time series with a high level of accuracy, but did provide a better fit to observed data during the critical August-October period of interest (see below).

- ***Downstream Temperature Boundary***

Hourly Lake Washington temperature profiles for specifying the downstream boundary were unavailable, with the exception of the records provided by the ACOE for the Kenmore buoy (8/18-12/22/99). The best available temperature profile information consists of monthly grab profile observations recorded at the North End Lake Washington Station (0804) near Kenmore as part of King County's long term lakes monitoring program. Detailed profile information (samples from 1, 4 and 8 m depth) going back to 1996 were used to develop a 4 year downstream stratified boundary temperature time series. This time series was then repeated (beginning with the appropriate year to account for leap years) to generate a long-term downstream temperature boundary condition.

- ***Additional Monitoring Data***

Additional tributary and mainstem (Marymoor only) monitoring data were also obtained from D.

Houck, KCDNR Wastewater Treatment Division (WTD) (pers. comm.). These data are being collected as part of the County's ongoing Habitat Conservation Planning (HCP) activities. However, data collection in the Sammamish River basin did not begin until late 1999. Therefore, these data will be most useful in the setup and testing of the model for the 2000 calendar year.

- ***Selection of Long Term Modeling Period***

Evaluation of the available data and consideration of model run time indicated that the most reasonable period for long-term modeling was 1970-1999 — a 30 year time history. This period was selected as the most representative of current basin flow conditions due to the uncertainty in the weir stage-discharge relationship prior to 1964 (Funke, D., pers. comm.). A 30-year simulation required approximately 14 hours of clock time on a Gateway E-4400 personal computer equipped with a 1 GHz Pentium processor.

Because the HSPF tributary basin flow models do not consider changes in land use or land cover over time, the model is not expected to accurately reproduce the actual 30-year river temperature time history. Instead, the use of the observed 30-year meteorological time history (primarily rainfall and air temperature) is intended to incorporate the natural climatic variability under reasonably current land use conditions in the basin. Incorporation of natural climate variability is expected to improve the confidence in model-predicted comparisons between the existing condition base case and temperature management alternatives.

Analysis of Model Output Relevant to Salmon

In order to provide comparisons among modeling scenarios that were most relevant to the exposure of salmon to heat stress, daily temperature threshold exceedances were combined with the duration of the exceedances to provide an Index of Thermal Stress (ITS). This approach essentially produced degree-day values above a chosen threshold—in this case 17 ^{o}C. As a simple example, a two-hour exceedance at 19 ^{o}C [2/24 x (19-17) = 0.168 degree-days] would count as four times as much thermal stress in this index as a one-hour exceedance at 18 ^{o}C [1/24 x (18-17) = 0.042 degree-days]. The resulting daily degree-day values were then summarized for the period August through October (the relevant chinook and sockeye spawning migration period in the Sammamish River) over each 30-year model run. Summary statistics included the average daily degree-day value (i.e., the sum of each daily-degree value divided by the number of days between August and October during the simulation period [2,760 days]) and the maximum daily degree-day value for the 30-year simulation period (i.e., the worst day during August through October during the simulation period [worst of 2,760 days]).

The threshold of 17 ^{o}C was chosen based on a literature review performed by the Washington Department of Ecology (Hicks 2000). The Ecology report cites 17 ^{o}C as the "Most Recommended Value" to support the summer migrations of chinook and sockeye (Hicks 2000, p. 100), which are the most relevant species and life stage for this analysis in the Sammamish River. This threshold was confirmed for use in the ITS by ecologists working on the river (Lucchetti, G. and Martz, M., pers. comm.).

Evaluation of Model Performance

Model calibration was re-evaluated using the same error statistics computed as part of the previous study (Jain et al. 2000): average hourly bias and hourly root mean square error (RMSE) (see Results section below). Graphical comparison of model output and observed temperatures are also provided in the appendix to this memo. Note that this information provides only a portion of the information needed to establish the acceptance of a model and its applications. The ultimate acceptance of a model requires evaluation of a host of factors and no specific pass/fail criteria exist. In general, model performance was considered adequate for conducting the alternatives analyses described in this report.

In addition to model error statistics, a limited number of model sensitivity analyses were conducted. The sensitivity analyses focused on the uncertainty associated with the downstream Lake Washington water surface elevation and temperature boundary conditions. The results of these analyses are summarized and discussed below.

Description of the CE-QUAL-W2 Model

CE-QUAL-W2 Version 3.0 has been recently released for beta testing and includes a number of improvements over the previous Version 2.0 releases (Cole and Wells 2000). These improvements include:

- Ability to model sloping river reaches
- Ability to model combinations of river, reservoir, and estuarine waterbodies
- Turbulence closure models for each waterbody using eddy-viscosity mixing length models
- Varying vertical grids between waterbodies
- Chezy or Manning's friction factor
- Reaeration formulae based on riverine or reservoir/lake or estuary character or user-defined formulations
- Evaporation models based on theory or user defined formulations
- Numerical algorithms for pipe, weir, and pump flow within or between waterbodies
- The effect of hydraulic structures on gas transfer and total dissolved gas transport
- Conservation of longitudinal momentum at intersections between main branches and side branches
- The effect of lateral inflows from tributaries or the lateral component of inflows from branch intersections on the vertical eddy viscocity
- Multiple user defined algal groups (up to six)
- Multiple user defined organic matter groups (up to nine)
- A simple routine to reduce segment-specific incident solar radiation to account for the effect of riparian or topographic shading on the heat balance

The latest improvements and proposed model features (see below) make CE-QUAL-W2 well suited for application to temperature problems in the Sammamish River.

Further model enhancements are proposed, although no specific time frame has been identified for addition of the following:

- A dynamic shading model dependent on topographic and vegetative shading for each segment
- Complex sediment diagenesis model to improve the reliability of long term water quality modeling where sediment-water interactions are important
- Incorporation of the water quality and hydrodynamic effect of macrophytes and periphyton
- A k-ϵ turbulence model that will collapse all turbulent eddy viscocity formulations into one
- User-defined number of organic matter fractions, algal groups, or arbitrary constituents as desired

Temperature Management Alternatives

The base case and fifteen management scenarios tested are described below:

Base Case - The Base Case consisted of the latest version of the Sammamish River W2 model that continuously simulates mainstem river water temperatures. The Base Case model also includes a 5 cfs "surface" withdrawal (July-August) from the bottom of river segments 13, 15, and 20 to represent existing point withdrawals. Withdrawals increase linearly from 0 cfs on April 30 to 5 cfs on July 1. Withdrawals decrease linearly from 5 cfs on August 31 to 0 cfs on October 1. Conceptually, it was assumed that the distributed flow in the calibrated model accounts for current groundwater withdrawals and resulting diversion of a portion of the groundwater flow to the river.

Fifteen management scenarios were simulated. These scenarios are described below.

Elimination of Existing Withdrawals

1. **Eliminate Existing Withdrawals vs. Base Case-** Eliminate existing surface withdrawals and introduce a maximum groundwater flow of 5 cfs distributed over model segments 2 - 24 (from Marymoor Park to downtown Woodinville) to simulate groundwater augmentation from terminating existing groundwater withdrawals along this reach of the river. The temperature of the additional groundwater is assumed to be 13 ^{o}C. Groundwater flow will mimic the pattern of the existing surface withdrawals (i.e., ramp up from 0 cfs to 5 cfs during May-June, peak at 5 cfs from July-August, and ramp down to 0 cfs by Oct 1).
2. **Eliminate Existing Withdrawals vs. Doubled Surface Withdrawal** - Evaluate possible effect of underestimating surface withdrawal. Create a revised Base Case with a maximum surface withdrawal of 10 cfs (same ramping pattern as above). Compare this case to the results for Alternative 1 to evaluate the effect of eliminating a larger surface withdrawal along with terminating groundwater withdrawals.

Groundwater Augmentation

3. **Small Groundwater Augmentation-** Simulate the potential effect of augmenting groundwater recharge. Introduce to the base case a steady year-round groundwater flow of 5

cfs distributed over model segments 2 - 24 to simulate additional groundwater recharge along this reach of the river. The temperature of the additional groundwater is assumed to be 13 ^{o}C.

4. **Large Groundwater Augmentation-** Same groundwater recharge case as Scenario 3 but with a steady year-round groundwater flow of 15 cfs distributed over model segments 2 - 24. The temperature of the additional groundwater is assumed to be 13 ^{o}C.
5. **Warmer Groundwater Augmentation** - Same groundwater recharge case Alternative 4, but the temperature of the groundwater inflow to the river was set at 16 ^{o}C (to reflect the possibility that augmented groundwater may not be as cool as existing groundwater).

Riparian Vegetation

6. **50% "Shade"** [1] – 50 percent total reduction in solar radiation, representing mature riparian plantings. This may be an optimistic maximum for shade given the width of the river, its angle to the sun and human uses still anticipated in the buffer area, including the trail (Lombard, J., pers. comm.). Riparian plantings might result in modification of localized climate (e.g., lower air temperature), but for now these effects are not assumed in the model.
7. **25% "Shade" –** 25 percent total reduction in solar radiation, representing mid-stage growth of riparian plantings.

Bear Creek Management

8. **Increased flows from Bear Creek of up to 5 cfs (Bear Creek Restoration)** - Assumes replacing existing withdrawals with other sources, including possible savings from conservation. The additional flow in Big Bear Creek increases linearly from 2.5 cfs beginning in May to a maximum of 5 cfs in July-August and decreases linearly to 2.5 cfs by October 1. The additional 2.5 cfs flow occurs from October 1 through April 30 of the following year.
9. **Increasing temperature of Bear Creek (Lost Bear Creek Shade) –** Increased temperature of Big Bear Creek, resulting from reduced shade as existing riparian areas along the stream are reduced or removed (a management scenario to be avoided, evaluating risk from inadequate protection of vegetation). The synthesized long term Big Bear tributary temperatures were adjusted through the use of the Response Temperature Model and its shading coefficient to produce a maximum difference of 2 ^{o}C during the maximum temperature period in 1999. The model was then run using the modified tributary temperature for this tributary.

Combination of Alternatives

10. **Eliminate withdrawals plus Bear Creek Restoration –** Eliminate existing surface withdrawals as in Alternative 1 and Bear Creek Restoration as above.
11. **Eliminate withdrawals plus large groundwater augmentation** - Eliminate existing surface withdrawals as in Alternative 1 and large (15 cfs at 13 ^{o}C) groundwater augmentation as in Alternative 4 above.

[1] A simplified approach to simulating the effect of riparian shade on incoming solar radiation is currently used in CE-QUAL-W2 version 3.0. The addition of a dynamic shading model is planned for a future release of CE-QUAL-W2.

12. **Eliminate withdrawals, large groundwater augmentation, and Bear Creek restoration** - Eliminate existing surface withdrawals as Alternative 1, large (15 cfs at 13 ^{o}C) groundwater augmentation as in Alternative 4, and Bear Creek restoration as above.
13. **Eliminate withdrawals, large groundwater augmentation, Bear Creek restoration, plus 25 % shade** - Eliminate existing surface withdrawals as Alternative 1, large (15 cfs at 13 ^{o}C) groundwater augmentation as in Alternative 4, Bear Creek restoration and 25 % "shade" as above.

Hypolimnetic Withdrawal

14. **Hypolimnetic Withdrawal from Lake Sammamish Scenario 1** - Represents construction of a hypolimnetic withdrawal system in Lake Sammamish. The hypolimnetic temperature input is based on available monthly temperature profile monitoring data. Reliable hypolimnetic data for the Mid-Lake Lake Sammamish stations [North (0611) and South (0612)] go back as far as 1994 corresponding to the implementation and use of electronic temperature profiling equipment. Review of the 1999 profile data for the two mid-lake stations indicated that the bottom temperatures became relatively uniform at and below the 15-m depth. Due to the limited length of the available temperature record, a representative 30-year time history was constructed using the 99 percent upper confidence limit of the monthly mean temperatures recorded at 15-m depth at Station 0611 from 1994 to 2000 (Table 1). It was assumed that hypolimnetic temperatures do not fluctuate significantly on an hourly basis (fairly reasonable) and that linear interpolation between monthly values would provide a suitable test of the potential influence of this management scenario on river temperatures. Scenario 1 assumes that 10 cfs of hypolimnetic water are blended with the existing lake weir outlet flow during the critical August-October period. This alternative assumes that no existing flow is diplaced. The temperature of the weir flow decreases and the existing flow is increased by 10 cfs..
15. **Hypolimnetic Withdrawal Scenario 2 –** This scenario assumes that 20 cfs of hypolimnetic water is blended with the existing weir outlet flow to reduce the outlet temperature without any change in the existing flow rate. This scenario is more optimistic (i.e., will result in greater predicted cooling) than the previous scenario due to the higher hypolimnetic withdrawal rate and the greater influence of replacing a portion of the warm outlet flow vs. adding additional cool water to the existing warm outflow.

Selected Locations for Management Evaluation

A total of six model grid locations were selected for purposes of calculating the ITS and comparison of management alternatives. All temperature differences were based on comparison with model predictions from the **bottommost** model layer, assuming that salmon will seek the coolest available water. The model segments selected were as follows:

- Segment 3, upstream of Bear Creek
- Segment 6, downstream of Bear Creek (after inflow has mixed and "reset" river temperature)
- Segment 20, NE 145th Street (north end of Agricultural Production District)
- Segment 25, The segment just above the confluence with Little Bear Creek

- Segment 37, Blyth Park (typically the coolest point of the river in summer)
- Segment 43, Swamp Creek mouth (after river has warmed from lake backwater)

Table 1. Summary Statistics for Lake Sammamish Hypolimnetic Temperatures (°C) at 15 m depth – August-October 1994-2000

	August	September	October
Mean	9.9	9.9	10.7
Standard deviation	0.46	0.65	1.5
n	7	5	6
Minimum	9.4	9.2	9.6
Maximum	10.6	10.8	13.7
95 % UCL	10.3	10.8	12.3
99 % UCL	10.5	11.3	13.2

UCL = Upper Confidence Limit
Statistics derived from monthly temperature profiles measured at the northern Lake Sammamish mid-lake station 0611.

Results

The model prediction errors associated with model reconfiguration and the use of additional/improved data and the results of the temperature management alternative simulations are summarized below.

Model Reconfiguration and Calibration

Changes in the model configuration and input files resulted in a general reduction in average hourly model prediction bias and hourly RMSE, except for the bias of predictions at the 124th Street and 145th Street bridges and RMSE at 145th Street Bridge, which increased (Table 2). Note that the comparison is based on the June-September period selected by JEEAI for calculation of error statistics.

Table 2. Comparison of Hourly Model Error Statistics for the June-September 1999 calibration, °C

	KCDNR (Jun – Sept 99)		JEEAI (Jun – Sept 99)	
Station	**Bias**	**RMSE**	**Bias**	**RMSE**
Railroad Bridge	0.03	0.31	0.17	0.33
Willows Run (51N)	0.07	0.35	-	-
NE 116th Street	-0.02	0.40	-0.20	0.56
NE 124th Street	0.13	0.46	-0.01	0.66
NE 145th Street	0.26	0.59	0.11	0.58
Blyth Park	-0.12	0.50	-0.13	0.61
Overall	0.06	0.43	-0.01	0.56

Notes: Willows Run (51N) temperature record was for the period 4/30/99 to 10/11/99. Problems with the Blyth Park thermistor resulted in a record for the period 6/1/99 to 8/25/99. Willows Run (51N) temperature records were not available to JEEAI for comparison to their model results.

The hourly average bias and hourly RMSE associated with the current model configuration and setup for the 1999 period of record and the critical period for management alternatives evaluation (August-October) are shown in Table 3. Model bias and RMSE for the entire period of record (June-October) was similar to the June-September period, except for the bias of predictions at the 124th Street and 145th Street bridges, which decreased. The bias and RMSE associated with the August-October period was generally higher, except for the bias of predictions at the 124th Street and 145th Street bridges. Plots of the hourly observed and model-predicted 1999 August-October temperatures at the six observation locations are provided in Appendix Figures A1 through A6. Figures that show the model fit to the entire period for which data are available and summary tables of the model setup and model coefficients are available upon request.

Table 3. Model Error Statistics for the Entire 1999 calibration, °C

	Jun - Oct 1999		Aug – Oct 1999	
Station	**Bias**	**RMSE**	**Bias**	**RMSE**
Railroad Bridge	-0.02	0.32	-0.06	0.36
Willows Run (51N)	0.02	0.33	0.02	0.39
NE 116th Street	-0.08	0.43	-0.15	0.48
NE 124th Street	0.06	0.48	0.00	0.53
NE 145th Street	0.17	0.58	0.09	0.59
Blyth Park	-0.12	0.50	-0.18	0.56
Overall	0.01	0.44	-0.05	0.48

Notes: Willows Run (51N) temperature record was for the period 4/30/99 to 10/11/99. Problems with the Blyth Park thermistor resulted in a record for the period 6/1/99 to 8/25/99.

The model reconfiguration also improved the match of model-predicted to observed surface water temperatures recorded during the September 2, 1999 FLIR study[2] (Figure 3). The FLIR study provided the most recent data indicating that summer surface water temperatures in the lower river increase downstream of North Creek. This phenomenon was also observed during a two-year study of the Sammamish River conducted in the late 1960s (Dalseg and Hansen 1969). Figure 3 shows the initial JEEAI model result based on the addition of two downstream model segments to the original 43 segment single reach (slope = 0.0000687 m/m) geometry and the result of widening and deepening the downstream model reaches (Buchak et al. 2001). Figure 3 also shows the result of dividing the original geometry into two waterbodies separated below segment 34 upstream of Blyth Park.

Note that the figure displays the FLIR-observed surface temperatures (at approximately 14:30 Pacific Standard Time [PST]), output from the model surface layer at the same time, and the temperature observations taken below the water surface at six locations along the river at 14:00, 15:00 and 16:00 PST. Field observations indicate that the river above Little Bear Creek is

2 The Excel spreadsheet supplied with the Watershed Sciences, LLC report (McIntosh and Faux 1999) indicates that the FLIR survey was conducted between 22:22 to 22:40 Greenwich Mean Time (GMT). Since GMT is 8 hours ahead of PST, the correct period for comparison of model results is 14:22 to 14:40 PST (or approximately 14:30 PST).

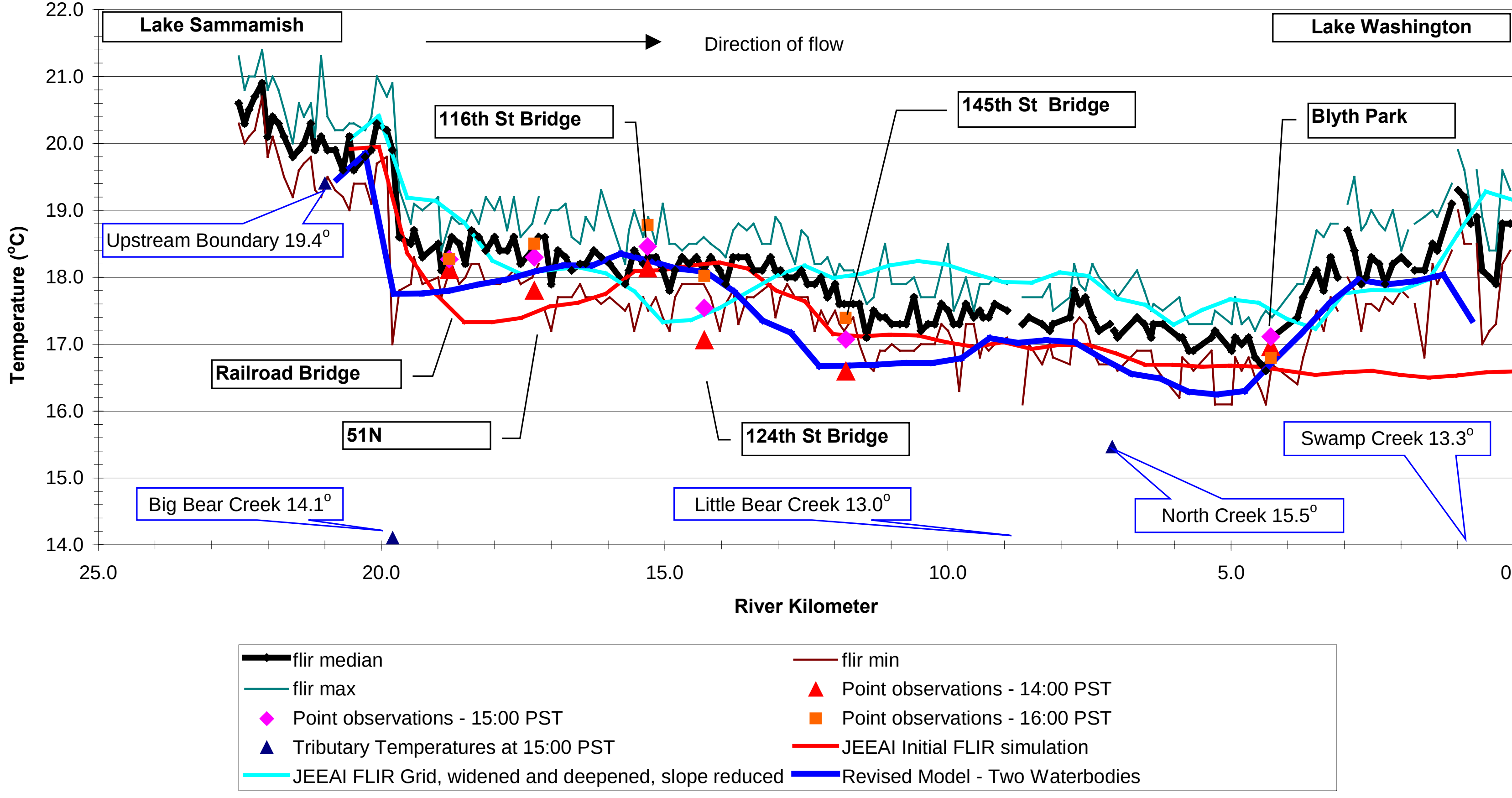

Figure 3. Comparison of Revised Model and JEEAI Model Simulations to the September 2, 1999 Forward-Looking Infrared (FLIR) Data. [Note: FLIR minimum, maximum, and median temperatures represent 10 sample points taken longitudinally along the center of the stream channel from every 4th color coded thermal image derived from the raw thermal images. Point observations and tributary temperatures based on sensors placed below the water surface at the identified locations.]

relatively unstratified (Houck, D., pers. comm.). Therefore, the FLIR observations in the upper river reaches represent the mixed river temperatures. However, the model predicts that the river becomes thermally stratified downstream of North Creek as the river deepens and slows due to the backwater effect of Lake Washington. The deepening and slowing of the river allows for greater solar heating of surface waters and development of thermal stratification. A recent field study (August 30, 2001) confirmed the warming of surface waters downstream of North Creek and the occurrence of thermal stratification in the downstream reach of the lower river.

Although the model currently reproduces the general surface warming and development of stratification in the downstream river reach, sufficient data have not yet been collected that would allow further calibration and testing of the model in this reach. The interactions of tributary and main stem flow and temperature with the backwater effect of Lake Washington are complex. Therefore, the model predictions in this reach, particularly for segments 37 and 43 considered in the evaluation of the temperature management alternatives, should be viewed with caution. Collection of additional temperature data suitable for calibration of the model to the stratified temperature conditions in the lower river is recommended.

Model Sensitivity Analyses

Limited model sensitivity analyses were conducted to evaluate the potential effect of 1) systematic error in the downstream water surface elevations recorded by the Corps of Engineers at Kenmore and 2) the effect of using continuous vs. monthly temperature profile data for the downstream boundary condition.

- ***Kenmore Water Surface Elevation***

To evaluate the potential effect of systematic error in the Kenmore water surface elevation, two additional model runs were conducted by increasing and decreasing the water surface elevation by 0.1 m (0.3 ft). These model runs indicated that river temperatures as far upstream as Blyth Park can be affected as much as 0.5 ^{o}C by a 0.1 m change in the downstream elevation boundary condition (figure available upon request). Therefore, it is recommended that the uncertainty in the Kenmore water surface elevation be evaluated as part of further model refinement.

- ***Downstream Temperature Profiles***

To evaluate the potential effect of using monthly vs. continuous temperature profile data at the downstream boundary, one additional model run was conducted using only monthly temperature profile data (North End Lake Washington Station 0804) as the downstream temperature boundary condition. Comparison with the model predictions based on the Corps of Engineers 1999 continuous temperature data indicated that model temperature predictions at the most downstream model segment were relatively sensitive to the downstream temperature boundary condition (maximum difference of 1.2 ^{o}C at 4 m depth). However, the predicted temperatures at Blyth Park did not differ by more than 0.01 ^{o}C (figure available upon request). Therefore, the use of monthly grab temperature profile data from the North End Lake Washington Station 0804 appears reasonable for the evaluation of temperatures at or above Blyth Park.

Synthesis of Temperatures for Long Term Simulations

A table that summarizes the final calibration values used in the Response Temperature Model to synthesize long term tributary temperatures is available upon request. The average hourly bias and hourly RMSE associated with the synthesis of weir and tributary temperatures for the 1999 period of record and the critical period for management alternatives evaluation (August-October) are shown in Table 4. Plots of the hourly observed and model-predicted 1999 temperatures are available upon request.

Table 4. Temperature Synthesis Model Calibration Error Statistics, ^{o}C

	Annual 1999		Aug - Oct 1999	
Boundary Condition	**Bias**	**RMSE**	**Bias**	**RMSE**
Upstream Boundary (weir) – CE-QUAL-W2	-0.68	1.01	-0.63	0.86
Upstream Boundary (weir) – Response Model	-0.27	1.09	-0.67	1.21
Big Bear Creek	0.01	0.84	0.20	1.04
Little Bear Creek	0.04	0.75	0.29	0.82
North Creek	-0.31	1.08	-0.01	0.91
Swamp Creek	0.20	0.80	0.10	0.96

Notes: The weir temperature record was for the period 4/30/99 to 10/22/99. The weir temperature synthesis generated by the CE-QUAL-W2 model was used in the long term simulation of the Base Case. The remaining tributary temperatures were synthesized using the Response Temperature Model.

Average hourly Response Temperature Model tributary temperature prediction bias ranged from -0.28 to 0.05 and the hourly RMSE ranged from 0.76 to 1.00. Bias and RMSE for the August-October period was higher for Big Bear and Little Bear Creeks and lower for North Creek. Bias was lower and RMSE higher for Swamp Creek. The Response Temperature Models evidenced an overall positive prediction bias for Big Bear, Little Bear, and Swamp Creeks and a very slight negative bias for North Creek.

Temperatures that were predicted for the weir using the Response Temperature Model indicated a relatively higher bias and RMSE, likely due to the more complex processes that control the outlet temperature from Lake Sammamish. The average hourly Response Temperature Model bias on an annual basis for the weir was lower than for the outlet prediction from the Lake Sammamish CE-QUAL-W2 model. However, bias and RMSE for the August-October CE-QUAL-W2 modeling period was lower than that of the Response Temperature Model and qualitative comparison (figure available upon request) indicated that the CE-QUAL-W2 model has less negative bias at the end of the critical period in October.

In general, the potential negative bias in the synthetic long term weir temperature record should not affect relative comparisons between Base Case and temperature management alternatives as long as the management alternative does not involve manipulation of the weir temperature. This condition holds true for all but the hypolimnetic withdrawal alternatives analyzed. In the hypolimnetic withdrawal scenarios, the potential average bias of approximately –0.5 ^{o}C in the synthetic weir temperature is likely balanced somewhat by the selection of the 99 percent upper confidence limit of recorded hypolimnetic temperatures for the long term hypolimnetic withdrawal temperature input (see Table 1).

Synthesis of Tributary Flows for Long Term Simulations

Existing County watershed hydrologic models (HSPF) were used to synthesize the long-term time history of tributary flows. The average hourly bias and hourly RMSE associated with the HSPF models for the 1999 calendar year and the August through October period are shown in Table 5. Plots of the hourly observed and model-predicted 1999 tributary flows are available upon request.

Table 5. HSPF Model Error Statistics, cfs

	Annual 1999		Aug - Oct 1999	
Tributary	**Bias**	**RMSE**	**Bias**	**RMSE**
Big Bear Creek (02A at Union Hill Rd)	27	55	9	12
Little Bear Creek (30A at Highway 202)	1	23	2	9
North Creek (Snohomish Co. gage)	15	47	4	13
Swamp Creek (56B at 73rd Ave)	2	35	-5	11

Temperature Management Alternatives

The results of the Base Case and temperature management alternatives are summarized in Table 6. The summary table shows the average daily degree-day for the August-October period for 1970-1999 for the selected grid locations and the maximum daily degree-day for the same period. Table 7 provides the percent change in the average and maximum degree-day for each alternative in comparison to the Base Case, except for Alternative 2. Alternative 2 (maximum 10 cfs surface withdrawal) is a sensitivity test for the assumed rate of existing withdrawals. Therefore, Alternative 2 is most appropriately compared to Alternative 1 (elimination of existing withdrawals).

- ***Note on Interpretation of Management Alternative Results***

Though it is useful to understand the mathematical basis for the numbers in Table 6 shown for the Base Case and fifteen management alternatives (see example calculations for a hypothetical location and day in Figure 4), it is more important to understand the numbers in the context of the effects of thermal stress on salmon3.

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3 The reader should be cautioned that the long-term model results are based on synthetic tributary flow and temperature data. Therefore, the results are not intended to accurately represent temperature condtions in a particular year. The results are intended to capture the response of a number of temperature management alternatives under a wide variety of hydrologic and climatic conditions relative to the base case. Nonetheless, the Base Case results do provide a good indication of the magnitude and temporal variation of thermal stress.

Numbers shown as "Average" are averaged across a three month period (August to October) for 30 years. As an example, the daily average Index of Thermal Stress at Segment 3 (just below the weir) during August-October for the 30-year simulation period (and the overall average daily value) is shown in the top panel of Figure 5. Actual temperatures at segment 3 typically rise and fall as much as 2 ^{o}C over 24 hours, are greater than 17 ^{o}C over a 24-hr period in much of August, and typicallydecline from August to October.. The index number of 1.35 for the Base Case average at segment 3 (above Bear Creek), then, does not signify that 18.35 ^{o}C (1.35 above the 17 ^{o}C threshold) would be a typical temperature at segment 3 over the 30-year record of flow and weather conditions for August through October.. In the afternoon, segment 3 would typically be much warmer than 18.35 ^{o}C in August and much of September.

A 1.35 average index of thermal stress is a very high number, given the amount of time it implies adult salmon in that part of the river would endure temperatures that can be expected to do them physical harm—if not killing them outright, then increasing their susceptibility to disease and reducing the number and viability of their eggs for spawning. Even the 0.101 average index of thermal stress for the Base Case at Segment 37 is a cause of concern, recognizing that afternoon temperatures in August must typically be well above 17 ^{o}C to produce that average over the entire time period. Numbers shown as "Maximum" represent the single day with the highest index of thermal stress over the entire 30-year record (see bottom panel of Figure 5). Even they, however, represent the integrated temperature exceedances over a 24-hour period. Water temperatures were not typically 24.02 ^{o}C (7.02 above the 17 ^{o}C threshold) on the "Maximum" day for the Base Case at Segment 3—they were considerably higher than 24.02 ^{o}C in the late afternoon, and less than 24.02 ^{o}C in the early morning. Such temperatures can be lethal for salmon, especially if the days that follow are similar.

- ***Discussion of Results***

Note that in the management alternatives that reduce thermal stress in the upper river reaches, the average and maximum daily-degree day was almost always predicted to increase (i.e., increase stress) at segment 43. This was particularly true for the alternatives that resulted in an increase in flow in addition to a reduction in upstream river temperatures. In fewer cases where thermal stress was predicted to decrease in upstream reaches, the thermal stress was also predicted to increase at segment 37. As noted above, the thermal dynamics of the lower river reach is a complex interaction of main stem and tributary flow with the backwater produced by Lake Washington. Because the model has not been adequately calibrated to conditions in this reach, the predictions for segments 37 and 43 should be viewed with caution. Considering that the Base Case stress levels are lowest in this reach of the river (and that the absolute increases are relatively small [maximum difference of 0.003 and 0.20 for the average and maximum daily degree-day, respectively]), the direction and uncertainty of these predictions does not compromise the significance of the results reported for the upper river reaches.

Table 6. Summary of Average and Maximum Index of Thermal Stress (Daily Degree Day) for the Period August-October 1970-1999 as Predicted by the Sammamish River CE-QUAL-W2 Model.

	Segment 03		Segment 06		Segment 20		Segment 25		Segment 37		Segment 43		Average (n=6)	
Case	Average	Max.	Average	Max.	Average	Max.	Average	Max.	Average	Max.	Average	Max.	Average	Maximum
Base Case (5 cfs surface/5 cfs gw withdrawals)	1.35	7.02	0.691	5.56	0.611	5.78	0.405	4.99	0.101	2.65	0.028	1.96	0.53	4.66
Eliminate Withdrawals														
1) Elim. With. (No surface withdrawal/5 cfs gw return)	1.32	6.95	0.654	5.42	0.525	5.37	0.335	4.14	0.108	2.52	0.030	2.01	0.50	4.40
2) Mod. Base Case (10 cfs surface/5 cfs gw withdrawal)	1.35	7.02	0.691	5.56	0.605	5.76	0.404	5.22	0.088	2.63	0.027	1.92	0.53	4.68
Groundwater Augmentation														
3) 5 cfs 13 °C	1.32	6.95	0.651	5.42	0.514	5.34	0.329	4.24	0.099	2.50	0.029	1.99	0.49	4.41
4) 15 cfs 13 °C	1.28	6.84	0.579	5.14	0.370	4.60	0.220	3.58	0.085	2.54	0.030	2.05	0.43	4.13
5) 15 cfs 16 °C	1.31	6.89	0.635	5.27	0.497	4.99	0.316	3.94	0.108	2.66	0.031	2.04	0.48	4.30
Riparian Vegetation														
6) 50% "Shade"	1.33	7.00	0.642	5.40	0.357	4.97	0.139	3.05	0.016	1.33	0.015	2.01	0.42	3.96
7) 25% "Shade"	1.34	7.01	0.666	5.48	0.479	5.39	0.259	4.00	0.049	2.07	0.023	2.00	0.47	4.33
Bear Creek Management														
8) 5 cfs Flow Restoration	1.34	7.01	0.605	5.37	0.571	5.69	0.378	4.69	0.108	2.61	0.029	1.98	0.51	4.56
9) Effect of Lost Shade	1.35	7.02	0.787	5.81	0.665	5.98	0.434	5.13	0.106	2.73	0.028	1.96	0.56	4.77
Combined Alternatives														
10) Elim. With. / Bear Ck. Rest.	1.32	6.95	0.574	5.24	0.497	5.30	0.317	4.09	0.108	2.68	0.030	2.02	0.47	4.38
11) Elim. With. / Large GW Aug.	1.26	6.78	0.547	5.01	0.327	4.30	0.183	3.30	0.074	2.44	0.030	2.12	0.40	3.99
12) Alternative 11/Bear Ck. Rest.	1.26	6.78	0.485	4.87	0.318	4.29	0.174	3.23	0.069	2.38	0.031	2.15	0.39	3.95
13) Alternative 12 / 25% "Shade"	1.25	6.77	0.465	4.80	0.232	3.96	0.103	2.56	0.026	1.62	0.024	2.16	0.35	3.64
Hypolimnetic Withdrawal														
14) 10 cfs Added to Outlet	0.453	4.58	0.302	4.05	0.381	4.75	0.263	3.81	0.090	2.48	0.029	2.02	0.25	3.61
15) 20 cfs Blended w/ Outlet	0.047	3.31	0.050	3.07	0.124	3.51	0.097	3.13	0.045	2.02	0.025	1.99	0.06	2.84

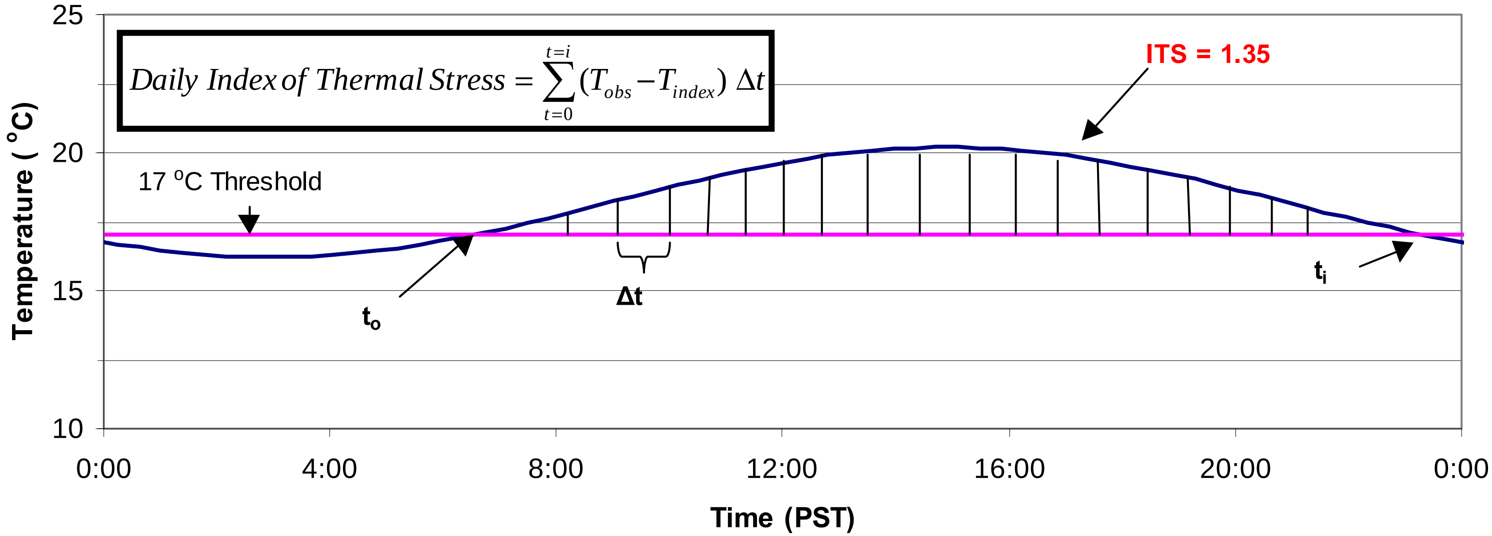
Notes:

Daily Degree-Days based on product of daily duration and magnitude of temperature exceedances greater than 17 °C. Temperature statistics derived from model output from the bottom active cell of the referenced model segments.

Table 7. Summary of Percent Change Relative to the Base Case in the Average and Maximum Index of Thermal Stress (Daily Degree Day) for the Period August-October 1970-1999 as Predicted by the Sammamish River CE-QUAL-W2 Model.

	Segment 03		Segment 06		Segment 20		Segment 25		Segment 37		Segment 43		Average (n=6)	
Case	Average	Max.	Average	Max.	Average	Max.	Average	Max.	Average	Max.	Average	Max.	Average	Maximum
Withdrawal Sensitivity Analysis														
2) Mod. Base Case (10 cfs withdrawal) [1]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1) Elim. With. (No surface withdrawal/5 cfs gw return)	- 1.6	- 1.0	- 5.4	- 2.6	- 13.2	- 6.8	- 17.0	- 20.6	+ 22.1	- 4.0	+ 8.9	+ 4.4	-5.8	-6.0
Alternatives Comparisons to Base Case														
Base Case (5 cfs surface/5 cfs gw withdrawals)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eliminate Withdrawals														
1) Elim. With. (No surface withdrawal/5 cfs groundwater return)	- 1.6	- 1.0	- 5.4	- 2.6	- 13.9	- 7.1	- 17.1	- 17.0	+ 6.6	- 4.8	+ 5.0	+ 2.2	-6.4	-5.6
Groundwater Augmentation														
3) 5 cfs 13 oC	- 1.8	- 1.0	- 5.7	- 2.5	- 15.9	- 7.5	- 18.6	- 15.1	- 1.9	- 5.8	+ 1.9	+ 1.6	-7.5	-5.4
4) 15 cfs 13 oC	- 5.1	- 2.6	- 16.2	- 7.5	- 39.3	- 20.4	- 45.6	- 28.2	- 16.4	- 4.0	+ 4.6	+ 4.7	-19.5	-11.4
5) 15 cfs 16 oC	- 2.9	- 2.0	- 8.1	- 5.1	- 18.6	- 13.7	- 21.8	- 21.1	+ 6.9	+ 0.3	+ 7.8	+ 3.8	-9.0	-7.8
Riparian Vegetation														
6) 50% "Shade"	- 0.9	- 0.3	- 7.1	- 2.8	- 41.6	- 14.0	- 65.7	- 39.0	- 84.1	- 49.8	- 46.9	+ 2.2	-21.4	-15.0
7) 25% "Shade"	- 0.4	- 0.1	- 3.6	- 1.4	- 21.6	- 6.6	- 35.9	- 19.9	- 51.6	- 22.0	- 20.0	+ 2.0	-11.5	-7.2
Bear Creek Management														
8) 5 cfs Flow Restoration	- 0.1	- 0.2	- 12.5	- 3.4	- 6.4	- 1.5	- 6.5	- 6.1	+ 6.2	- 1.6	+ 2.8	+ 1.0	-4.6	-2.2
9) Effect of Lost Shade	0.0	0.0	+ 13.9	+ 4.6	+ 8.9	+ 3.5	+ 7.4	+ 2.7	+ 4.3	+ 3.1	+ 0.5	- 0.1	+ 5.8	+ 2.4
Combined Alternatives														
10) Elim. With. / Bear Ck. Rest.	- 1.7	- 1.0	- 16.9	- 5.8	- 18.7	- 8.2	- 21.7	- 18.0	+ 6.9	+ 1.0	+ 7.3	+ 3.0	-10.5	-6.0
11) Elim. With. / Large GW Aug.	- 6.6	- 3.4	- 20.8	- 9.9	- 46.5	- 25.5	- 54.9	- 33.8	- 27.4	- 8.0	+ 7.5	+ 7.8	-24.0	-14.3
12) Alternative 11/Bear Ck. Rest.	- 6.7	- 3.4	- 29.8	- 12.4	- 47.9	- 25.8	- 56.9	- 35.2	- 31.8	- 10.2	+ 9.0	+ 9.4	-26.7	-15.2
13) Alternative 12 / 25% "Shade"	- 7.0	- 3.6	- 32.7	- 13.6	- 62.1	- 31.5	- 74.6	- 48.7	- 74.2	- 38.7	- 14.7	+ 10.0	-34.0	-21.8
Hypolimnetic Withdrawal														
14) 10 cfs Added to Outlet	- 66.4	- 34.8	- 56.4	- 27.1	- 37.5	- 17.8	- 34.9	- 23.6	- 11.1	- 6.6	+ 2.9	+ 3.1	-52.3	-22.4
15) 20 cfs Blended w/ Outlet	- 96.5	- 52.9	- 92.8	- 44.8	- 79.8	- 39.2	- 76.1	- 37.2	- 55.6	- 23.7	- 11.3	+ 1.6	-87.8	-39.1

[1] The 10 cfs surface withdrawal case was designed to evaluate the effect of possibly underestimating existing surface withdrawals. The increased withdrawal case is a revised base case with a maximum surface withdrawal of 10 cfs (with the same ramping pattern as the Base Case). This case is most appropriately compared to the Withdrawal Elimination Alternative 1 to evaluate the effect of eliminating a larger surface withdrawal along with terminating groundwater withdrawals.



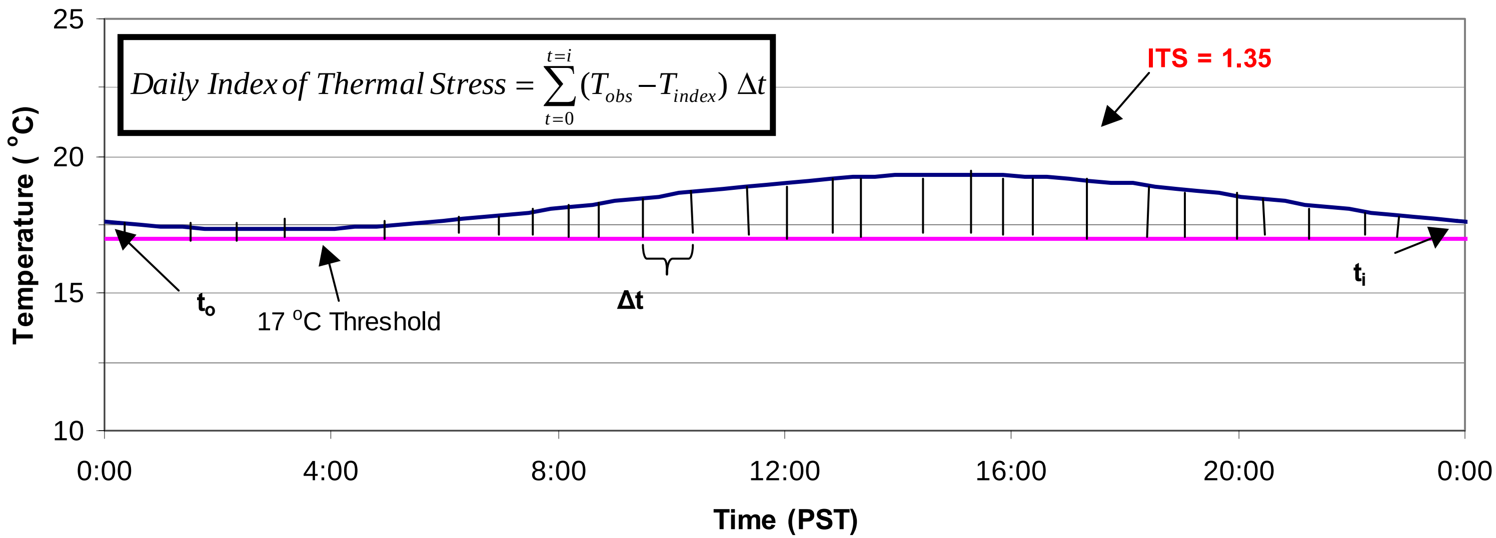
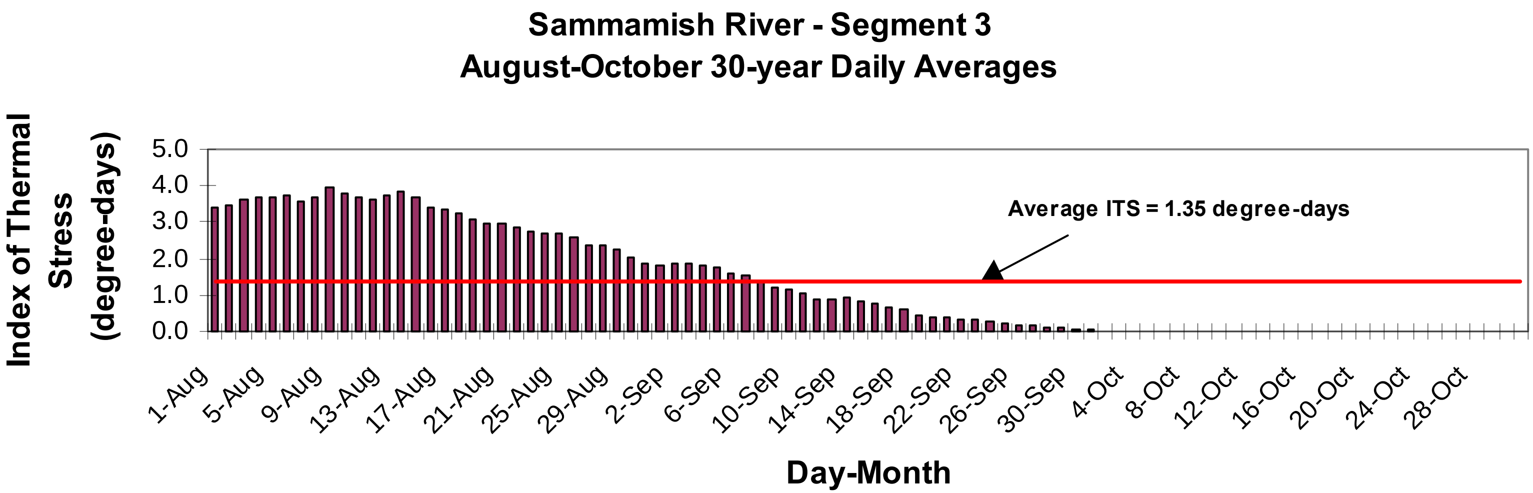


Figure 4. Example Calculations of an Index of Thermal Stress Equal to 1.35 Degree-Days. [Note: The top figure shows a diurnal temperature fluctuation of 4 °C (average =18.2 °C) and the bottom figure shows a fluctuation of 2 °C (average =18.3 °C). The actual model calculations were conducted at intervals of 15-seconds or less.]



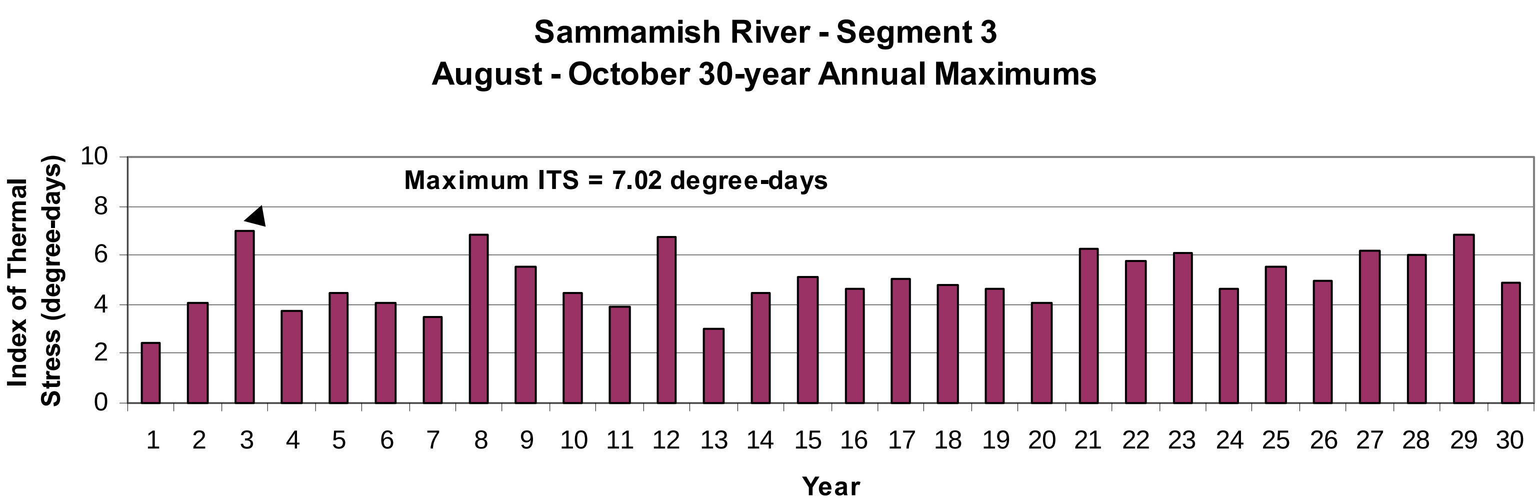


Figure 5. Summary of Daily Average and Annual Maximum (August-October) Index of Thermal Stress at Segment 3 over 30-year Simulation Period for the Base Case.

***Base Case*:** The Base Case results indicate that the greatest thermal stress for salmonid migration occurs in the vicinity of the upstream boundary. Thermal stress then decreases as a function of downstream distance. The average daily degree-day declines from 1.35 at model segment 3 to less than 0.03 at the most downstream evaluation segment 43. The maximum daily degree-day declines from 7.02 to 1.96 at the same locations.

***Sensitivity to Existing Withdrawal Estimate*:** Changing the maximum Base Case withdrawal from 5 to 10 cfs has little or no measurable effect at the most upstream locations (segments 3, 6, and 20), but does slightly increase the maximum daily degree-days at segment 25 (increase of 4.6 %) (see Table 6). The average daily degree-days actually decreases at segments 37 and 43 (12.9 and 3.5 %, respectively) relative to the Base Case, due to the increased influence of cool tributary inputs from Little Bear and North Creeks as a result of reduced upstream flow (i.e., the effect of greater upstream withdrawals). Comparison of the percent change in the Index of Thermal Stress between the Base Case and Alternative 1 and Alternative 2 (revised base case) and Alternative 1 (see Table 7), indicates that the expected change in thermal stress is generally very similar. However, there is a greater predicted increase in the average daily degree day at Segment 37 (+22.1 vs. +6.6 percent) when elimination of withdrawals (Alternative 1) is compared to a 10 cfs maximum withdrawal base case (Alternative 2). Again, this difference is due to the interaction of upstream withdrawals with the influence of cooling derived from the inputs of downstream tributaries.

Because the evaluation of management alternatives is based on the relative difference between the Base Case and alternatives model runs, the small differences between the 5 and 10 cfs model runs in the lower river model reaches should not raise too great a concern over the uncertainty of existing withdrawals. The results also indicate that the uncertainty in existing withdrawals is of relatively small consequence for the prediction of upstream reach temperatures.

***Eliminate Existing Withdrawals*:** Eliminating existing withdrawals is predicted to increasingly reduce thermal stress beginning at the head of the river as the cumulative effect of cool groundwater return distributed over segments 2-24 reduces river temperatures. The largest reduction in thermal stress is predicted to occur just below the region of enhanced groundwater inflow at segment 25— a 17.1 and 17.0 % decrease in the average and maximum daily degree-day, respectively.

***Groundwater Augmentation*:** The direct augmentation of groundwater flow to the river over the same reach also provided a cumulative benefit beginning at the head of the river. The greatest overall reduction in thermal stress was predicted for augmentation with 15 cfs of groundwater at a temperature of 13 ^{o}C. The largest reduction in thermal stress for this alternative is predicted to occur just below the region of augmented groundwater inflow at segment 25— a 45.6 and 28.2 % decrease in the average and maximum daily degree-day, respectively.

***Riparian Vegetation*:** The "Shade" alternatives also produced a gradually increasing benefit beginning with small reductions in thermal stress at Segment 3 and increasingly larger reductions downstream. The greatest overall reduction in thermal stress occurred in downstream reaches 20 to 43 due to the cumulative effect of shade on downstream temperatures. The largest overall reduction in thermal stress is predicted to occur at Segment 37 – a 84.1 and 51.6 % decrease in the average daily degree-day for the 50 and 25 % “Shade” alternatives, respectively.

***<u>Bear Creek Management</u>*: Reducing existing withdrawals in the Big Bear-Evans Creek basin, is predicted to result in a significant reduction in thermal stress just below the creek confluence with the Sammamish River— a 12.5 and 3.4 % decrease in the average and maximum daily degree-day at segment 6. However, the relative benefit appears to diminish considerably downstream.

The evaluation of the potential negative effect of reducing existing riparian shade in Big Bear Creek indicates that increasing daily maximum Bear Creek temperatures by as much as 2 ^{o}C would increase thermal stress below Bear Creek as far downstream as segment 37. The largest increase in thermal stress would occur immediately downstream of the confluence with the Sammamish River — a 13.9 and 4.6 % increase in the average and maximum daily degree-day at segment 6.

***<u>Combined Alternatives</u>*:**
Possible combinations of the above alternatives were also evaluated (i.e., Alternatives 10 through 13 described above). Generally, the greater the number of combined alternatives, the greater the predicted decrease in thermal stress, although combinations that included alterations in flow resulted in small increases in predicted thermal stress in the downstream reach associated with segment 43.

***<u>Hypolimnetic Withdrawal</u>*:**
Because the temperature of the Lake Sammamish hypolimnion at 15 m is almost always below 14 ^{o}C, the effect of these management alternatives appear to have the potential to greatly reduce thermal stress in the uppermost reaches of the Sammamish River (see Table 7). These alternatives also showed similar or less potential to reduce thermal stress at locations downstream of segment 6. The hypolimnetic withdrawal scenarios also showed the greatest potential river-wide reduction in thermal stress. An average reduction of 52.3 percent in the average daily degree-day was predicted for the most conservative hypolimnetic withdrawal scenario (Hypolimnetic Withdrawal Alternative 14 - addition of 10 cfs of cool hypolimnetic water to the existing river inflow).

Regardless of potential uncertainties in the analysis of the hypolimnetic withdrawal alternatives (see discussion on page 20 of this memo), the relatively significant reduction in thermal stress in the upper river reaches can not be dismissed.

***<u>Summary of Results</u>*:** Of the positive individual Sammamish River management alternatives evaluated (not including hypolimnetic withdrawal), the 50 % “Shade” alternative appears to provide the greatest overall reduction in thermal stress in downstream segments 20 to 43 (41.4 to

84.1 % reduction in average degree-days) due to the cumulative effect of segment shading on stream temperatures. However, the greatest benefit from shade occurs in the lower river reaches where the thermal stress is lower. Alternative 4 (groundwater augmentation of 15 cfs at 13 ^{o}C) provided the greatest overall reduction in thermal stress in upstream segmentss 3 and 6, including the greatest reduction in maximum degree-days at segment 20 (20.4 %). Overall, these two alternatives (i.e., shade and groundwater augmentation) provided very similar average benefits river-wide based on the average change in thermal stress at the six model segment evaluation locations; -19.5 and –21.4 percent in the average daily degree-day for Alternative 4 (large groundwater augmentation) and 50% “Shade”, respectively (see Table 7). The combination of withdrawal elimination, large groundwater augmentation, Bear Creek restoration and 25% “Shade” resulted in the greatest overall reduction in river-wide average stress (-34.0 percent in the average daily degree-day).

The effect of reducing existing withdrawals in the Big Bear-Evans Creek basin, also results in a significant reduction in thermal stress just below the creek confluence with the Sammamish River— a 12.5 and 3.4 % decrease in the average and maximum daily degree-days at segment 6. However, the benefit appears to diminish considerably downstream.

Hypolimnetic withdrawal provides the greatest benefit where it is needed most, in the upstream reach that receives the warm surface water outflow from Lake Sammamish. The less conservative strategy of adding 10 cfs of cool hypolimnetic water to the existing lake outflow is predicted to reduce the average and maximum thermal stress at Segment 3 by 66.4 and 34.8 %, respectively. The next greatest benefit at Segment 3 was achieved by the combination of all alternatives, including 25% “Shade” (Alternative 13) – a reduction of 7.0 and 3.6 % in the average and maximum thermal stress.

Recommendations

As a result of the knowledge base and experience gained from the refinement and application of the Sammamish River temperature model a number of recommendations for further model improvement can be made. Because the Sammamish River temperature model will also be incorporated into the SWAMP to link water quality models of Lakes Sammamish and Washington, further changes and additions to the model are also necessary. These changes primarily involve modification of the model geometry to facilitate linkages to the upstream and downstream lake models and development of the eutrophication, indicator bacteria, and toxics modeling components of the model.

Suggested field monitoring activities that would provide information to further improve and refine the temperature model include:

- Collection of additional downstream temperature profiles for further refinement and calibration of model predictions in the downstream river reach and improve our understanding of the stratified flow regime in the lower river
- Monitoring and evaluation of stratified temperature conditions in the lower river reach below

North Creek during critical conditions to provide data suitable for evaluation of the model predicted stratification in this reach.

- Establishment of mainstem continuous temperature monitoring stations for further calibration and refinement of model predictions
- Longitudinal synoptic temperature monitoring to further refine and calibrate model predictions over the entire river reach during critical conditions
- Groundwater studies to better estimate the spatial and temporal contributions of flow to the river including estimates of groundwater quantity and temperature.
- Additional low flow measurements at the weir to improve the low flow stage-discharge relationship
- Synoptic longitudinal observations of river water surface elevations during various flow regimes for model calibration and refinement
- Dye transport studies to provide travel time estimates for further model calibration

Suggested field monitoring activities that would provide information for the development of the Sammamish River eutrophication model include:

- Establishment of mainstem monitoring locations for water quality model calibration
- Periodic continuous measurements of dissolved oxygen and pH at representative mainstem locations to establish typical patterns of diurnal variation in these parameters.
- Addition of total organic carbon (TOC), dissolved organic carbon (DOC), and chlorophyll a to the County's existing routine tributary and Sammamish River mainstem monitoring program
- Evaluation of aquatic plant coverage and biomass and its potential influence on river water quality

Other recommendation include:

- Development of watershed models capable of accurately simulating tributary temperature and water quality inputs for the Sammamish River model, including distributed (ungaged) tributary inputs
- Further development of a Lake Sammamish water quality model to provide improved upstream boundary conditions to the Sammamish River model
- Further evaluation/correction/refinement of the Kenmore water surface elevations used for model calibration
- Develop interagency coordination and funding to compile, manage, and store a variety of climate data collected by various agencies and institutions in the region to facilitate the access and use of local climate information
- Develop and implement standardized procedures for the use of continuously recording thermistors to collect temperature data

The last recommendation should provide greater assurance that measured temperatures are representative of the actual well-mixed temperatures at each sampling location recorded with a documented time standard [e.g., Pacific Standard Time (PST)].

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